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DOCUMENTATION AND PRELIMINARY RESULTS OF THE SINGLE AXIS MOTION TESTS CONDUCTED ON THE NIMBUS-D ATTITUDE CONTROL SUBSYSTEM

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GREENBELT, MARYLAND

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ABSTRACT

The Engineering Model Nimbus-D Attitude Control System (ACS) was mounted on a single axis table about each of its control axes in turn. The table was supported by a torsion wire whose top end was restrained. For each axis, table rate and position errors were physically introduced and then the ACS was activated. These tests demonstrated that the ACS:

A. Was properly phased

B. Exhibited positive damping

C. Was able to transition from acquisition to fine control smoothly.

CONTENTS

TABLES

ILLUSTRATIONS

STATEMENT OF INTENT

The purpose of this report is to document the single axis motion tests performed on the Engineering Model ACS. Although the system exhibited stable, nominal behavior, this report is not intended to substitute for a detailed analysis of the system behavior observed.

REFERENCE DOCUMENTS

X-731-67-607: "Functional Description of The Attitude Control Subsystem for Nimbus-D"

X-731-68-504: "Nimbus-D Attitude Control System Engineering Model Hardware Simulation"

X-731-69-4: "Nimbus-D Attitude Control Subsystem Requirements Specification"

X-732-69-60: "Documentation of The Nimbus-D Initial Acquisition Study Simulation"

DOCUMENTATION AND PRELIMINARY RESULTS OF THE SINGLE AXIS MOTION TESTS CONDUCTED ON THE NIMBUS-D ATTITUDE CONTROL SUBSYSTEM

SINGLE AXIS FACILITY DESCRIPTION

The facility is housed in a closed structure (to minimize air current effects) roughly cubical 16 feet on a side in the high bay area of Building 22 at GSFC. A top restraint is provided for the 9 ft long, four strand Elgiloy Torsion Wire whose characteristics are as follows:

Spring Constant:	0.0167 in-oz/degree (August 1968)
(with pigtails):	0.0156 in-oz/degree (May 1969)
Strand Cross Section:	0.017" x 0.150"
Ultimate Strength:	368,000 psi
Yield Strength:	280,000 psi
Proportional Limit:	233,000 psi
Modulus of Elasticity:	29,500,000
Hardness (Rockwell C):	56 - 59

Surrounding the torsion wire, on a six inch diameter circumference, are 50 small wires wound in pigtail fashion (1/2" diameter) in order to provide minimum addition spring restraint to the table. These wires are used to provide: access to ACS test points, to externally control the table pneumatics (for initial condition introduction), to carry the ACS commands (including start signal), and to monitor the table battery voltage.

The table itself is all aluminum and consists of a square center section and four (4) bolts on arms. The overall table diameter is approximately 14 ft. These removable table arms provided a convenient means of adjusting the table inertia and supporting the table battery pack, 400 cps 2 phase clock, table rate gyro, and table pneumatics system. A commercial, non-Nimbus nitrogen pneumatics system was used because it provided a force couple and virtually eliminated any table translation when the pneumatic thrusters had occasion to fire. The table translation and pendulum action was limited to ±1/2° by a teflon "center bearing." This so-called center bearing was designed such that nothing touched (and resulted in frictional torques) until table pendulum action caused a table translation of 1/2° or more. The table balance was such that when this occurred, it occurred as a result of table pneumatics firing during acquisition when the resulting frictional torque was negligible. Great care and caution was taken so that no center bearing torques were exerted by the center bearing during all fine control runs. Figure 5 shows the table center bearing.

The table pneumatics torque level was set at 1 ft-lb (within 10%) by adjusting the orifices and pressure until a calculated jet activation time produced a calculated angular excursion when the table inertia was set at the appropriate Nimbus inertia. These inertias were set by mass adjustment and measurement of the torsional oscillation period. The resultant table inertias were very close to those of the Systems Requirement Document (X-731-69-4) and were as follows:

Roll:	311 slug-ft^2
Yaw:	131 slug-ft^2 (4% high)
Pitch:	[illegible]6 slug-ft^2

Figures 1, 2 and 4 show the general test configuration for the roll, yaw, and pitch tests respectively. The simulated earths that were used for roll and pitch tests (shown in Figures 1 and 4) represent a 600 nautical mile altitude. These targets were heated at a temperature equivalent to a 260° K earth. Figure 2 shows the general yaw test configuration; Figure 3 is included to document the physical positioning of the gyros on the ACS. An electro optical table position transducer was used for roll and pitch tests.

ROLL TESTS

An arbitrary matrix of 50 runs of various rate and position initial conditions was conducted. Table 1 lists the 50 runs and two basic measures of system performance:

A. Time to acquire to within 1°

B. Total gas expulsion time.

Runs 1 thru 14 can be compared with runs performed during the ACS hardware simulation study documented in X-731-68-504. The remaining runs can be compared with the fully computerized ACS orbital simulation conducted by the Nimbus-D Controls Task Force. In addition to the 50 runs listed in Table 1, a special long term stability run of 5 hours was conducted. The length of the run was limited by the table battery capacity. This run was started with a 90° offset and zero rate, and achieved pointing control better than ±1/2° for the entire

Table 1
Roll Test Summary

ϕ_o = Initial Roll Angle in degrees $\dot{\phi}_o$ = Initial Roll Rate in degrees/sec t_1 = Time to acquire to 1° in seconds t_2 = Total solenoid actuation time in seconds				
Run #	ϕ	ϕ°	t_1	t_2
1	-6	0	155	0.6
2	+6	0	112	2.0
3	-4	0	129	0.5
4	+4	0	34	0.06
5	-3	0	19	0.05
6	+3	0	15	0.0
7	-2	0	12	0.0
8	+2	0	7	0.0
9	+6	+1/2	73	2.1
10	+4	+1/2	122	1.6
11	+3	+1/2	194	1.7
12	-6	-1/2	122	1.4
13	-4	-1/2	150	0.6
14	-3	-1/2	142	2.0
15	+7	0	343	4.0
16	-7	0	208	3.0
17	+45	0	221	26.0
18	-45	0	186	27.0
19	+90	0	142	62.0
20	-90	0	182	59.0
21	-90	+1	263	57.0
22	-90	-1	222	54.0
23	+90	+1	192	84.0

Table 1 (Continued)

Run #	ϕ	$\phi°$	t_1	t_2
24	+90	-1	168	66.0
25	-45	+1	35	29.0
26	-45	-1	202	34.0
27	+45	+1	213	38.0
28	+45	-1	224	29.0
29	-7	+1	128	2.2
30	-7	-1	272	13.0
31	+7	+1	232	10.0
32	+7	-1	257	3.3
33	+7	+3	225	30.0
34	+7	-3	38	23.0
35	-7	+3	229	21.0
36	-7	-3	172	42.0
37	+45	+3	68	58.0
38	+45	-3	41	31.0
39	-45	+3	34	29.0
40	-45	-3	63	60.0
41	-45	+5	234	56.0
42	-45	-5	239	113.0
43	+45	+5	173	88.0
44	+45	-5	206	75.0
45	-7	+5	284	53.0
46	-7	-5	299	90.0
47	+7	+5	355	65.0
48	+7	-5	262	62.0
49	+90	+5	313	131.0
50	-90	-5	262	162.0

NOTE: The torsion wire null was aligned to within one (1) degree of the roll null for all runs.

period following acquisition. Strip chart recordings of appropriate roll test points and phase plane plots of all 50 runs are available for inspection in the Configuration Control Bank of the Nimbus-D Controls Task Force.

Figure 6 is a normalized plot of $\frac{\text{roll momentum}}{\text{roll error}}$ vs frequency obtained by electrically inserting an ac signal of 1/2° peak-to-peak amplitude into the roll attitude computer.

YAW TESTS

The methods used for yaw single axis motion testing were designed by P. S. P. Hui, Systems Analysis Section Head, Code 731. In general, they consist of using two "free" driving forces for the yaw fine control mode. These are the portion of earth's rate sensed by the RMP and the rate induced by the suspension system when the table is at positions other than the null of the suspension system. The earth's rate input is sinusoidal vs yaw position and the torsion wire input is linear vs table position. The yaw acquisition runs consisted of imparting 8 bipolar rates to the table via the table jets, activating the system, and continuing the problem until the table rate is reduced to less than 0.25 degrees/second and the yaw wheel is below its unloading level. These runs are summarized in Table 2 along with the time required to acquire (as defined above) and the total time of pneumatic expulsion.

Previous to beginning yaw fine control runs, the system was statically calibrated by measuring earth's rate by aligning the roll axis east-west, electrically biasing this out, and measuring the yaw angles required to achieve the yaw wheel deadbands. These static calibrations can be summarized as follows:

A. Roll Axis east-west, V_o @ J8-10 CLB = -495MV compared to -560MV calculated.

B. Yaw Angles required to achieve yaw wheel pulse modulator deadbands with earth's rate biased out were +8.0° and -8.2° compared to a calculated ±8.4°.

The results of these static calibrations are considered excellent. The electrical bias required to null out the residual component of earth's rate was maintained throughout the yaw fine control tests.

The yaw fine control runs are summarized in Table 2 and Figures 7 through 13. Runs I through V can be summarized as follows: the initial yaw angle and the position of the torsion wire null were chosen in such a manner that the table

Table 2
Yaw Test Summary

Acquisition			
$\dot{\psi}^o$ = Initial rate in degrees/seconds t_1 = Time to acquire in seconds t_2 = Total time of gas expulsion in seconds			
Run #	$\dot{\psi}^o$	t_1	t_2
1	+1/2	0.6	0.6
2	+1	1.1	1.1
3	+2	5.0	5.0
4	+3	7.4	7.4
5	+4	9.5	9.5
6	+5	11.9	11.9
7	+6	14.3	14.3
8	+9	20.4	20.4
9	-1/2	0.5	0.5
10	-1	1.1	1.1
11	-2	4.5	4.5
12	-3	6.8	6.8
13	-4	9.0	9.0
14	-5	11.1	11.1
15	-6	13.6	13.6
16	-9	18.6	18.6

Table 2 (Continued)

Fine Control					
Run #	ψ	Position of Wire Null	Length of Run	Control Rate (° /sec)	Peak-Peak Oscillation Reduction During Run
1	-16°	-17°	2.3 hrs	0.00048	—
2	+17°	+17°	2.1 hrs	0.00075	—
3	+16°	-17°	3 hrs	—	79%
4	-1°	-0.3°	0.8 hrs	0.00017	—
5	+90°	0°	3 hrs	0.0035	—
6	+90°	180°	1.6 hrs	0.016* avg	58%

*0.05 deg/sec rate electrically introduced

NOTES: 1. The stable earth's null is @ 180°.

2. Yaw Angle (ψ) is defined as being 180° when the positive roll axis is pointing east.

3. Initial rates $\approx$ 0 for all fine control runs.

would alternate between control by the torsion wire driving force and control by the ACS under the influence of earth's rate and the torsion wire dynamics. In general, the ACS allowed the table to move extremely slowly in the direction of the stable earth's null at rates consistent with the system deadbands until the yaw wheel saturated. When this occurred, the torsion wire took and held control until the table rate reversed and reduced to near zero at the sinusoidal peaks of table motion. This process then repeated itself until the batteries became discharged (typically 2 to 3 hours). Run IV is noteworthy in that it demonstrates that the ACS is capable of controlling rates to better than 0.0002 degrees per second. Run VI has the same characteristics as Runs I through V except that a large rate (0.05 degrees/sec) was electrically introduced to the ACS. As can be seen in Figure 12, this input produces a unidirectional rate influence of about 0.02 degrees/sec. It is felt that this measured rate has experimental error in it and that the actual rate is higher than what was actually measured.

Another feature worthy of note is the evidence of positive damping in the yaw loop apparent in Figures 9 and 12. Figures 7 through 12 treat the periods of torsion wire control as linear phenomia for simplicity. However, these are actually portions of sine curves as demonstrated by Figure 13 which is an expansion of an applicable portion of Figure 9.

As in roll, strip chart recordings of all yaw motion tests are available for inspection in the Nimbus-D Controls Task Force Configuration Control Bank.

PITCH TESTS

Ideally, due to the nature of pitch geometry, pitch motion testing is limited to initial errors of 10°. This is because the flat earth simulators used provided a good approximation to the actual three dimensional situation only within ±10°. However, due to the saturation characteristics of the pitch lead amplifiers, the test set-up was usable (and was used) for angles up to 45 degrees. The targets were heated to correspond to a 220° K earth. Also as before, initial conditions were physically introduced with the table jets, and then the ACS was activated. An arbitrary matrix of 36 runs was performed. Table 3 lists the 36 runs and two basic measures of system performance:

A. Time to acquire to within 1°

B. Total gas expulsion time.

As in roll, these runs can be compared to the hardware simulation study and the initial acquisition study. Strip chart recordings of ACS test points and phase planes for these runs are available for inspection in the Configuration Control Bank of the Nimbus-D Controls Task Force. Figure 14 is a normalized plot of $\frac{\text{pitch momentum}}{\text{pitch error}}$ vs frequency obtained by electrically inserting an ac signal of 1/2 peak-to-peak amplitude into the pitch attitude computer.

Cloud Tests

At the conclusion of pitch tests a cloud was introduced on the trailing horizon of the forward scanner. The cloud width was 25% of the earth width. The system ignored the cloud, and nulled well within 0.1 degree of the previous null.

Table 3
Pitch Test Summary

θ = Initial pitch angle in degrees
θ° = Initial pitch rate in degrees/seconds
t_1 = Time to acquire to 1° in seconds
t_2 = Total time of gas expulsion

Run #	θ	θ°	t_1	t_2
1	+4	0	44.4	0.0
2	+6-1/2	0	44.1	3.5
3	+9	0	32.5	3.2
4	-9	0	20.2	11.1
5	-6-1/2	0	66.6	8.0
6	-4	0	77.5	0.2
7	+4	+1/2	79.6	7.6
8	+6-1/2	+1/2	60.6	5.4
9	+9	+1/2	44.8	9.6
10	-4	-1/2	55.4	4.9
11	-6-1/2	-1/2	40.2	12.4
12	-9	-1/2	21.2	13.5
13	+10	+1	22.5	16.1
14	+5	+1	59.8	3.9
15	-5	+1	53.0	2.5
16	-10	+1	68.0	2.3
17	-10	-1	23.0	15.8

Table 3 (Continued)

Run #	θ	$\theta°$	t_1	t_2
18	-5	-1	24.2	12.9
19	+5	-1	31.6	3.6
20	+10	-1	64.8	7.6
21	+10	+3	64.0	16.9
22	+5	+3	32.0	21.0
23	-5	+3	48.5	17.7
24	-10	+3	78.2	24.8
25	-10	-3	65.0	43.0
26	-5	-3	88.4	25.0
27	+5	-3	54.5	29.4
28	+10	-3	99.0	37.8
29	+10	+4	30.0	22.6
30	+5	+4	98.5	40.9
31	-5	+4	48.0	31.6
32	-10	+4	85.0	46.4
33	+5	-4	89.8	47.0
34	+30	0	105.0	39.1
35	-30	0	45.0	35.4
36	-45	0	111.0	71.8

NOTE: The torsion wire null was aligned to within one degree of the pitch null for all runs.

CONCLUSIONS

These tests demonstrated that the ACS:

A. Was properly phased

B. Exhibited positive damping

C. Was able to transition from acquisition to fine control smoothly.

RECOMMENDATIONS

It is strongly recommended that the Engineering Model Hardware used in this task be made available to G. E. /MSD for comparative phasing tests with the Nimbus-D ACS Flight Hardware.

ACKNOWLEDGEMENTS

Several people of Code 732 at GSFC were of immense help in designing, fabricating, instrumentating, modifying, and using the single axis test facility that supported this task. They are as follows:

John Kelley, Joe Bentley, Robert Peterson, Charles Falkenhan, Ralph Harms, Alan Ott, and Ed Young.

Messrs. Peterson and Flakenhan participated strongly throughout the entire test sequence.

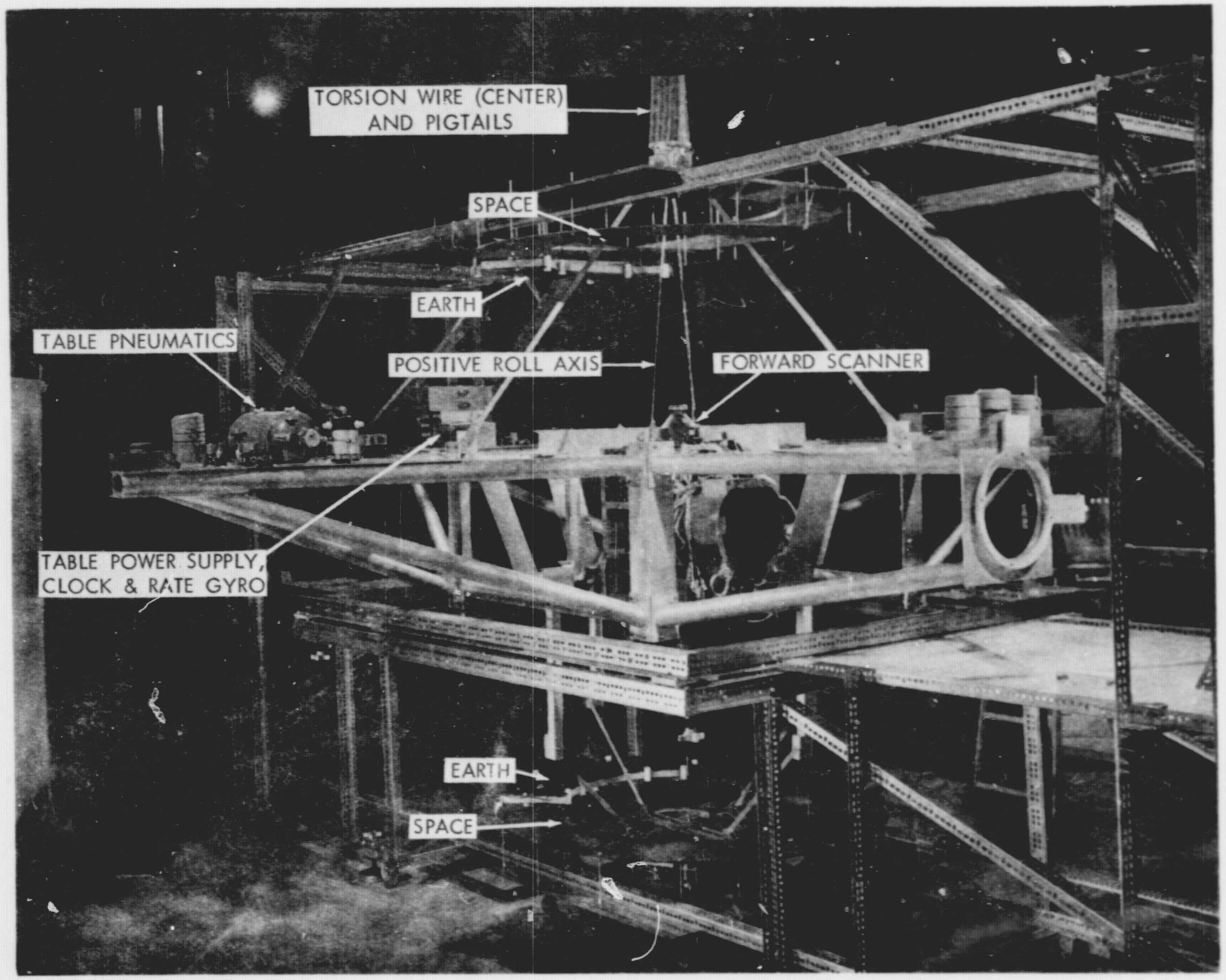

Figure 1. Roll Test Configuration

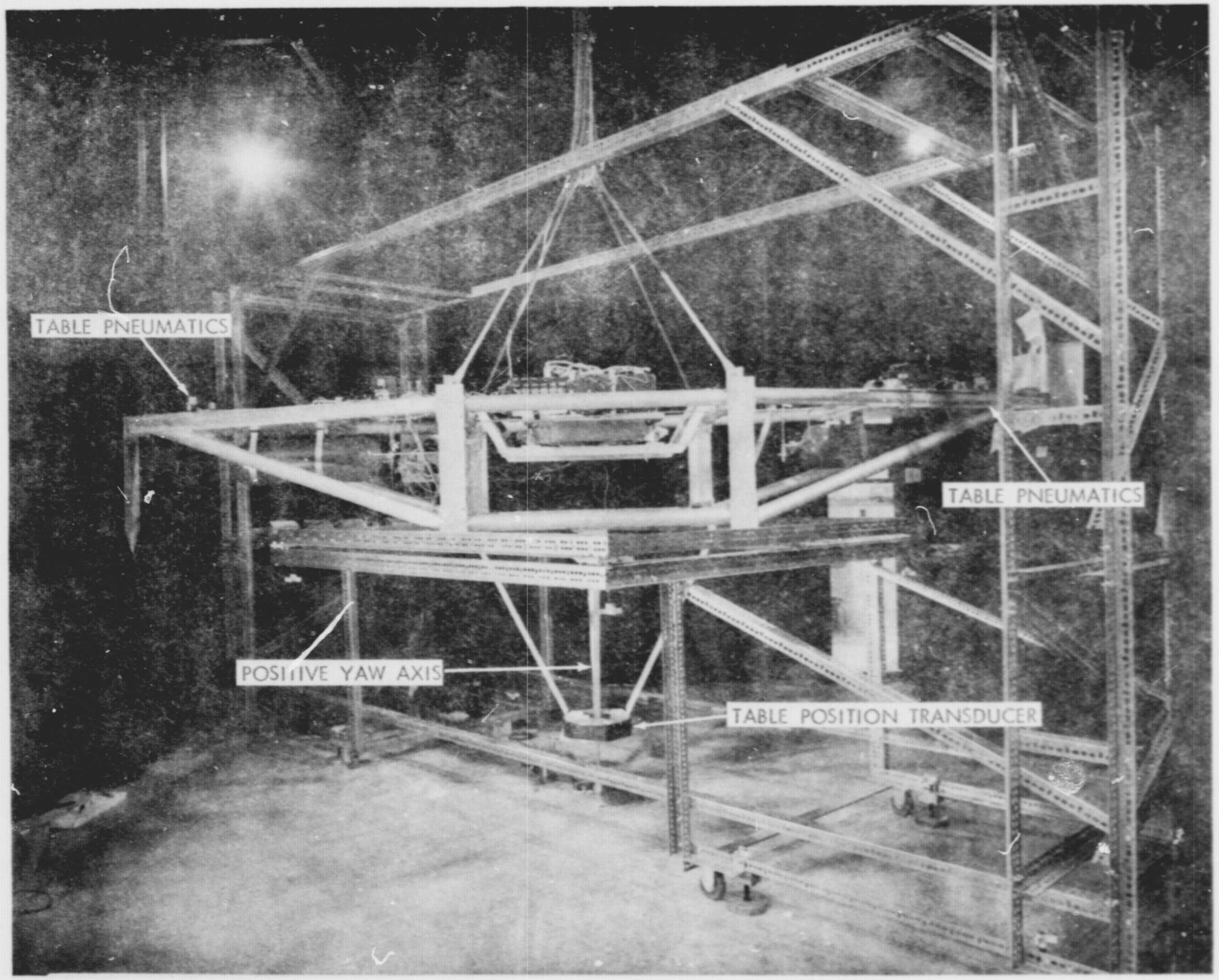

Figure 2. Yaw Test Configuration

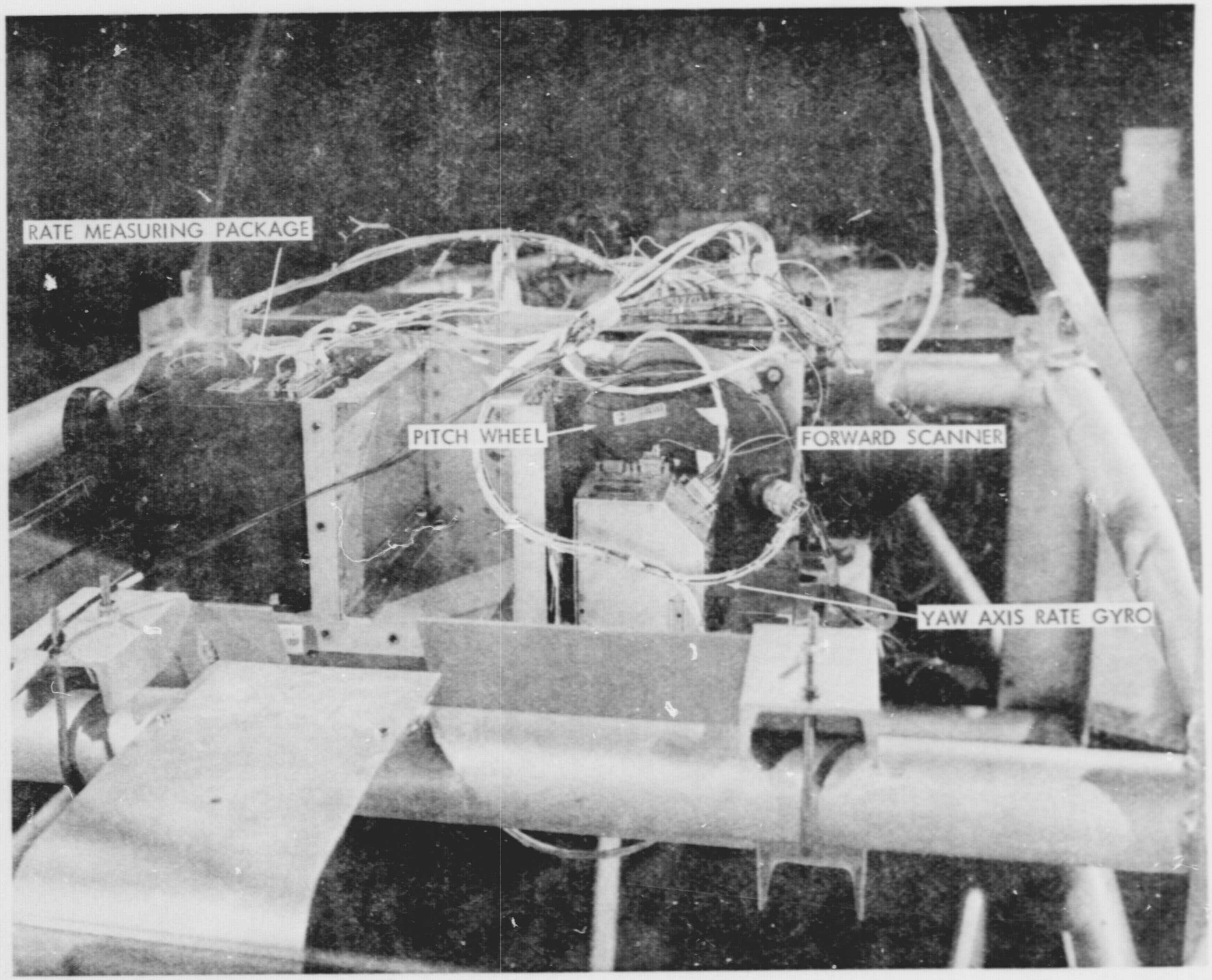

Figure 3. Yaw Gyro Orientations

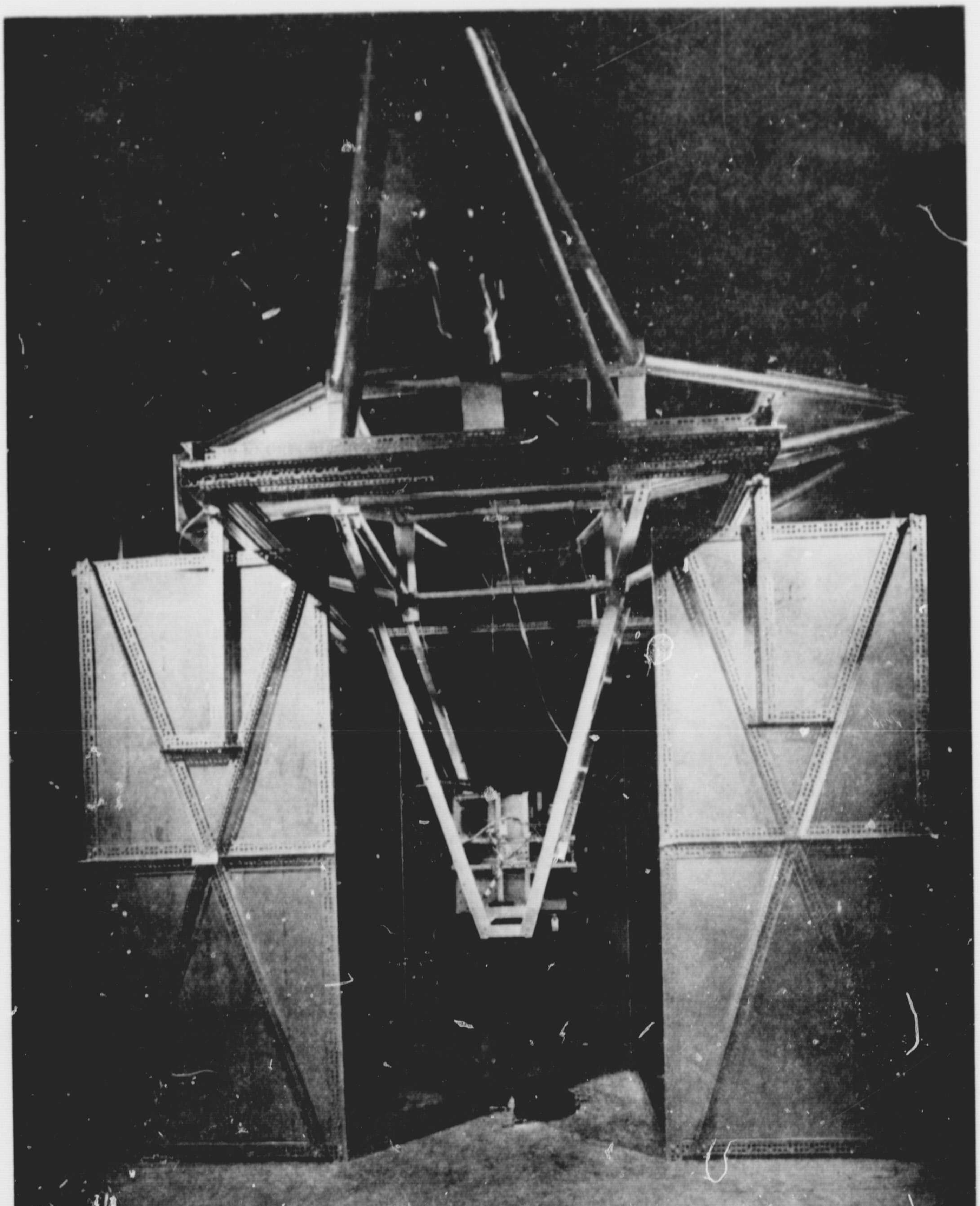

Figure 4. Pitch Test Configuration

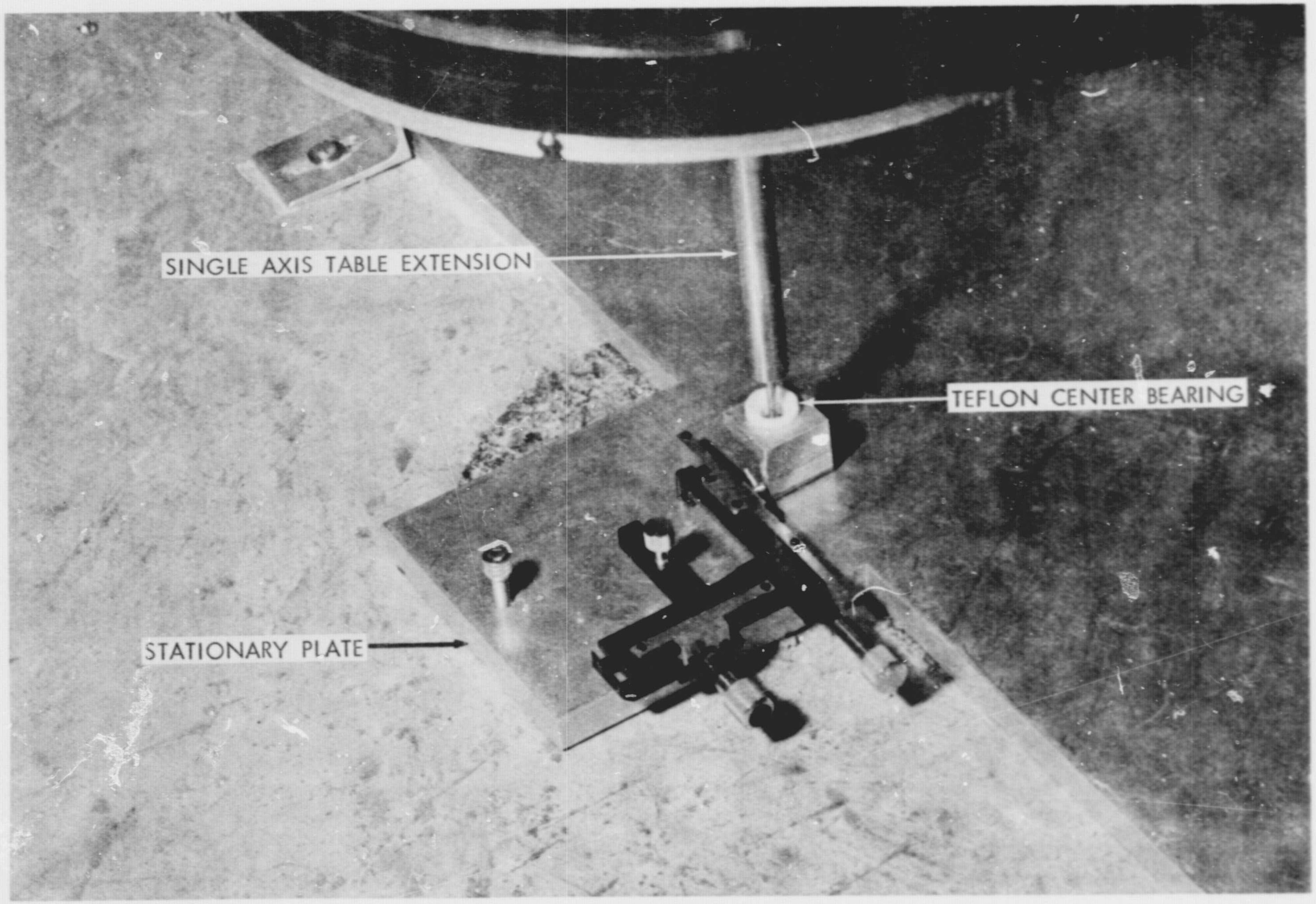

Figure 5. Single Axis Table Center Bearing

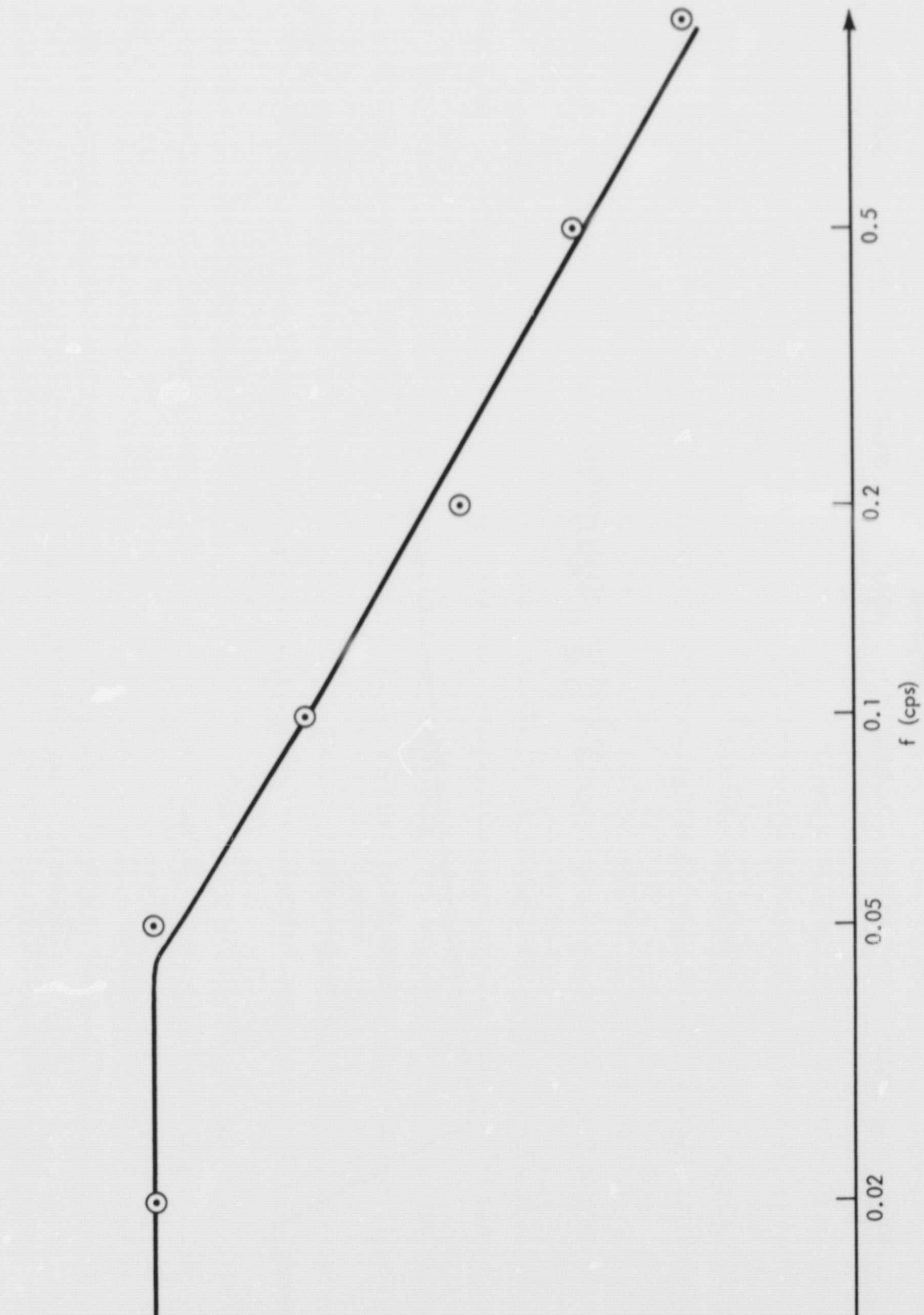

Figure 6. Roll Frequency Response

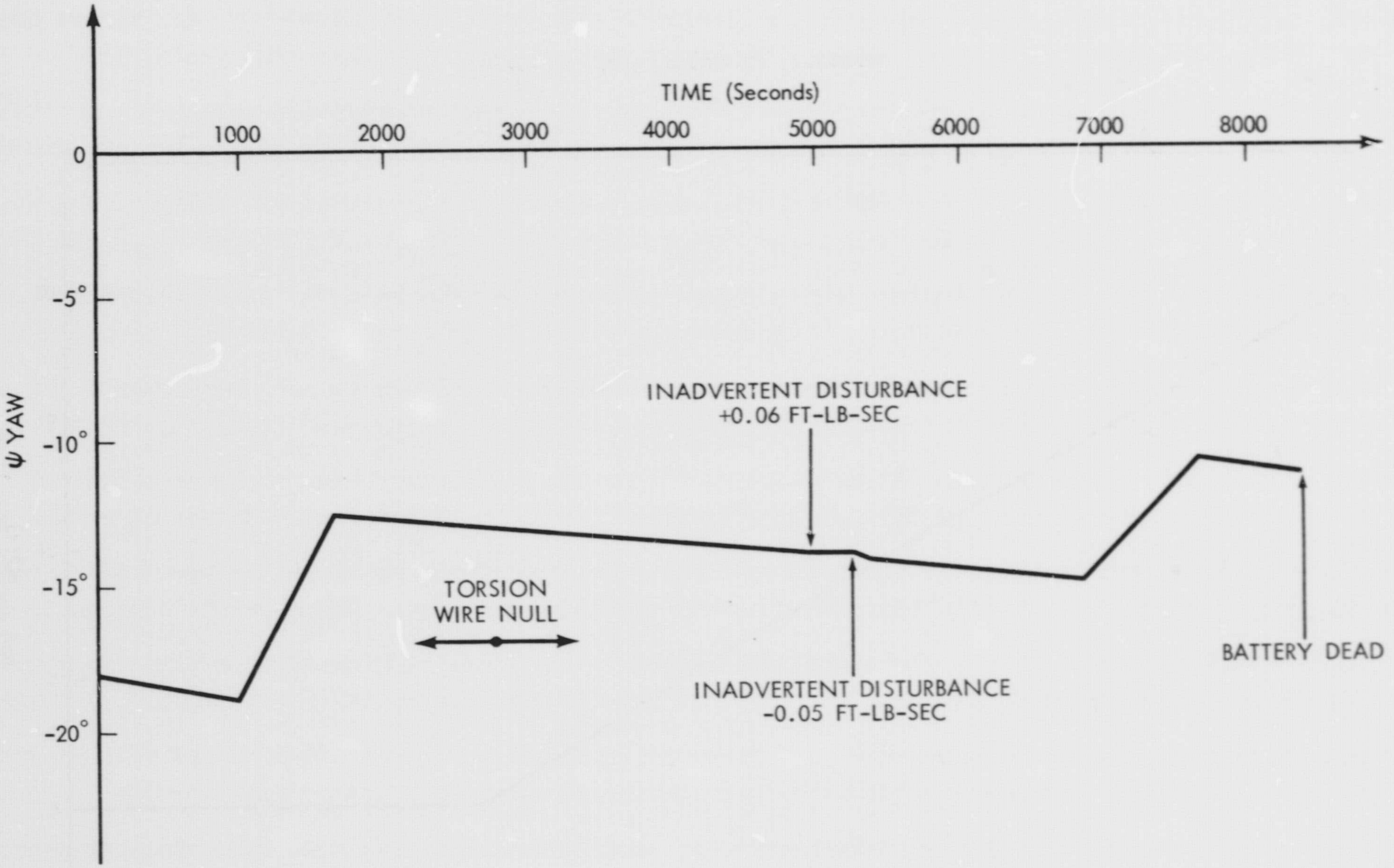

Figure 7. Yaw Fine Control Run I

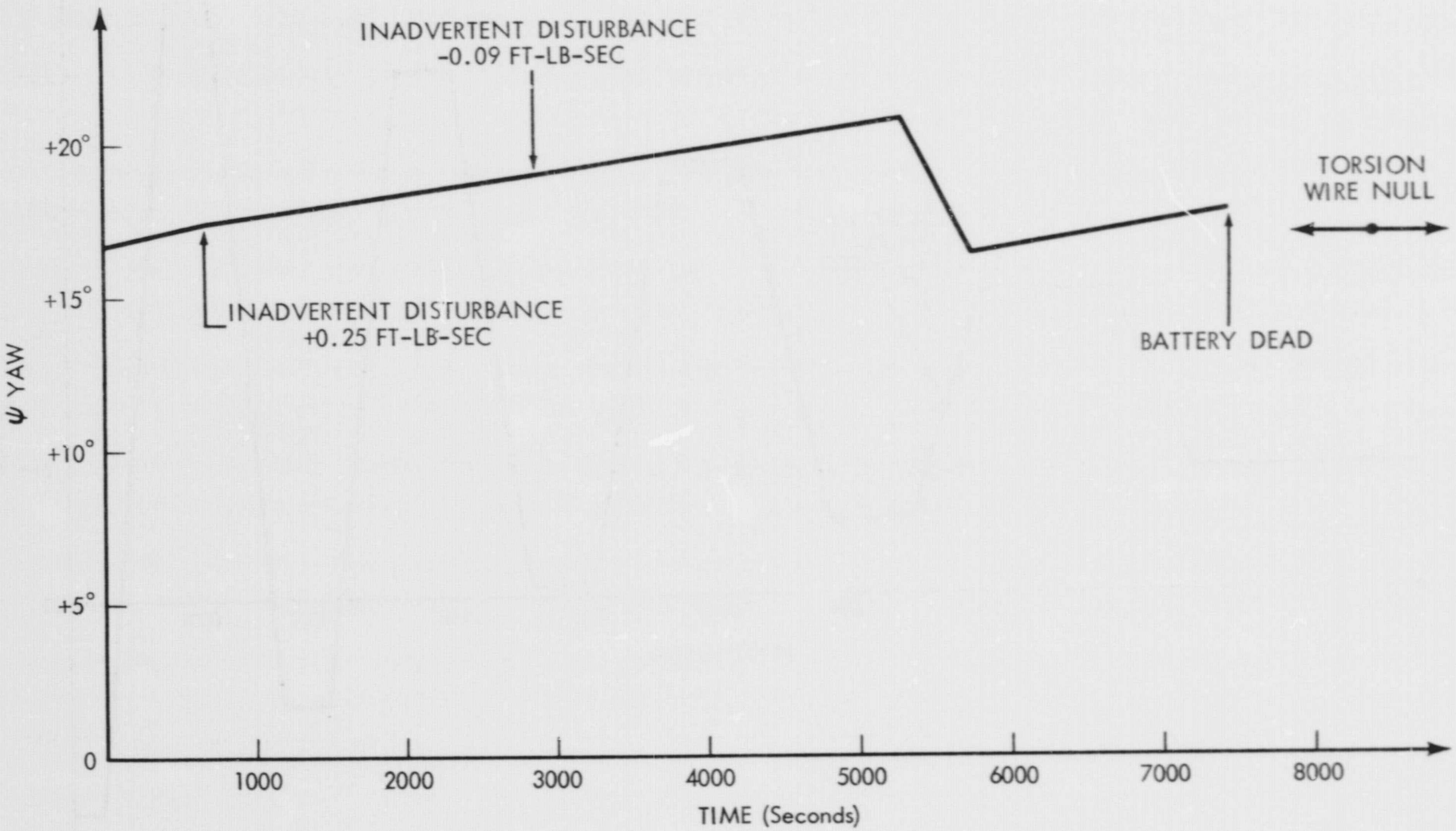

Figure 8. Yaw Fine Control Run II

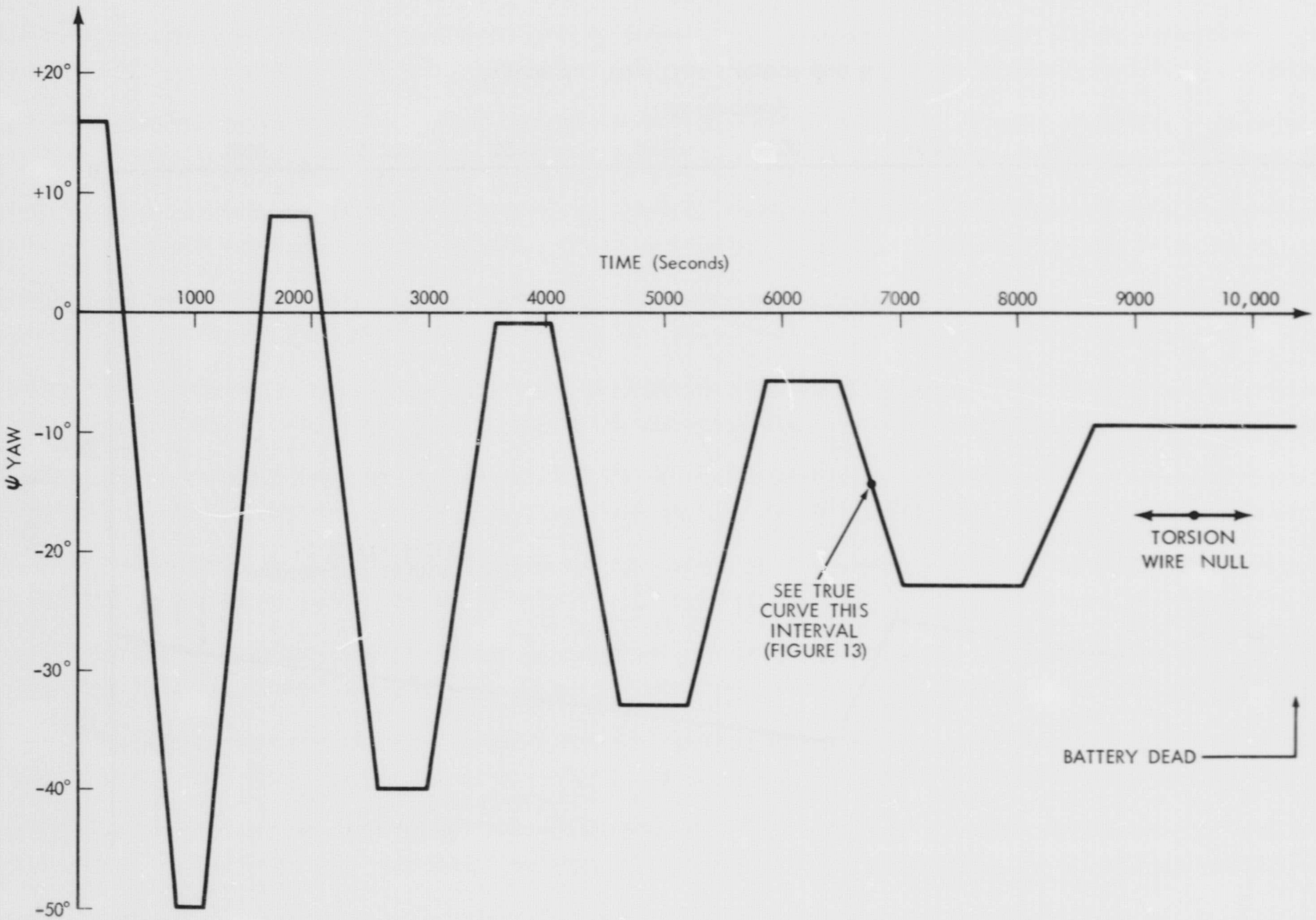

Figure 9. Yaw Fine Control Run III

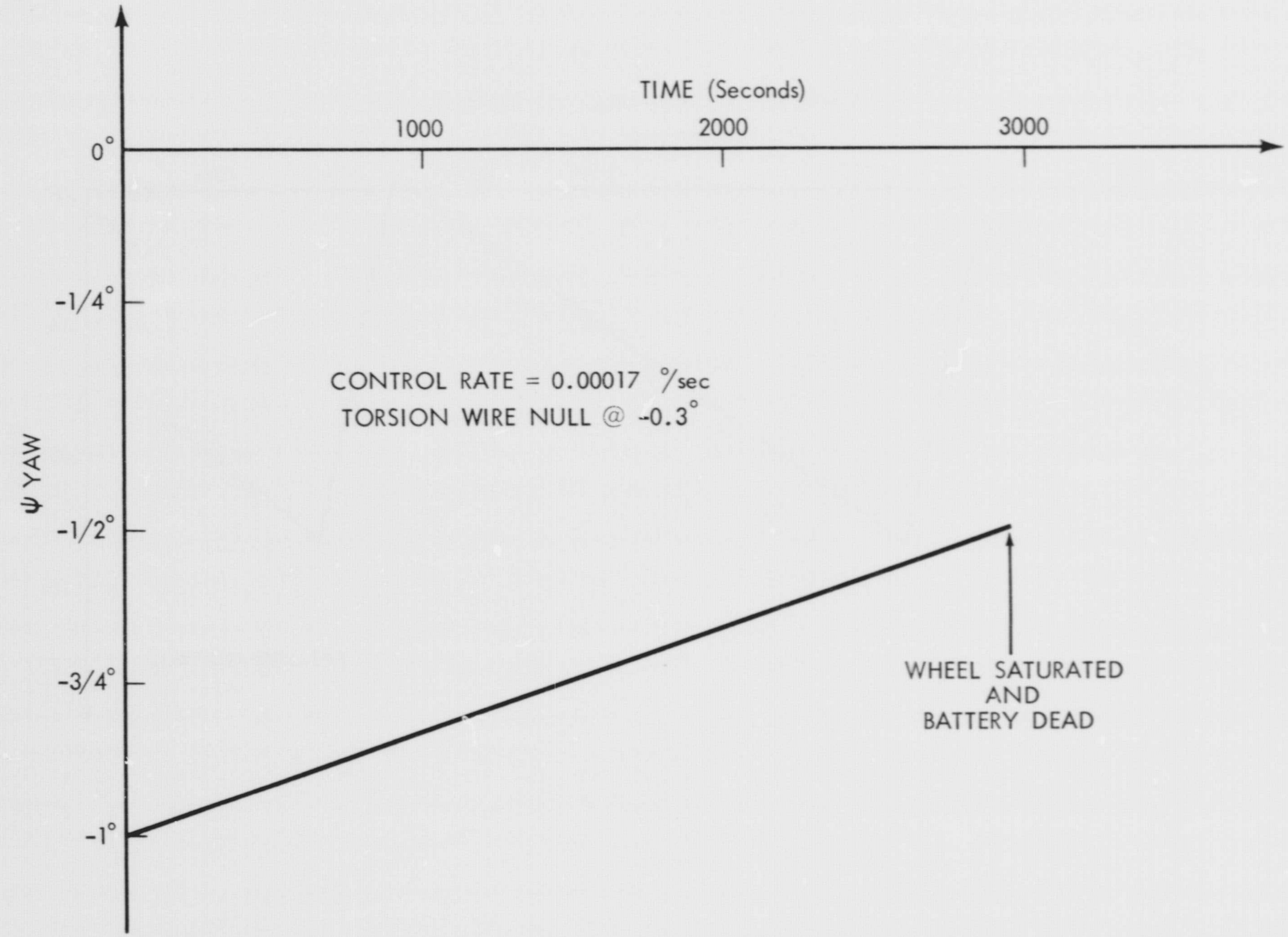

Figure 10. Yaw Fine Control Run IV

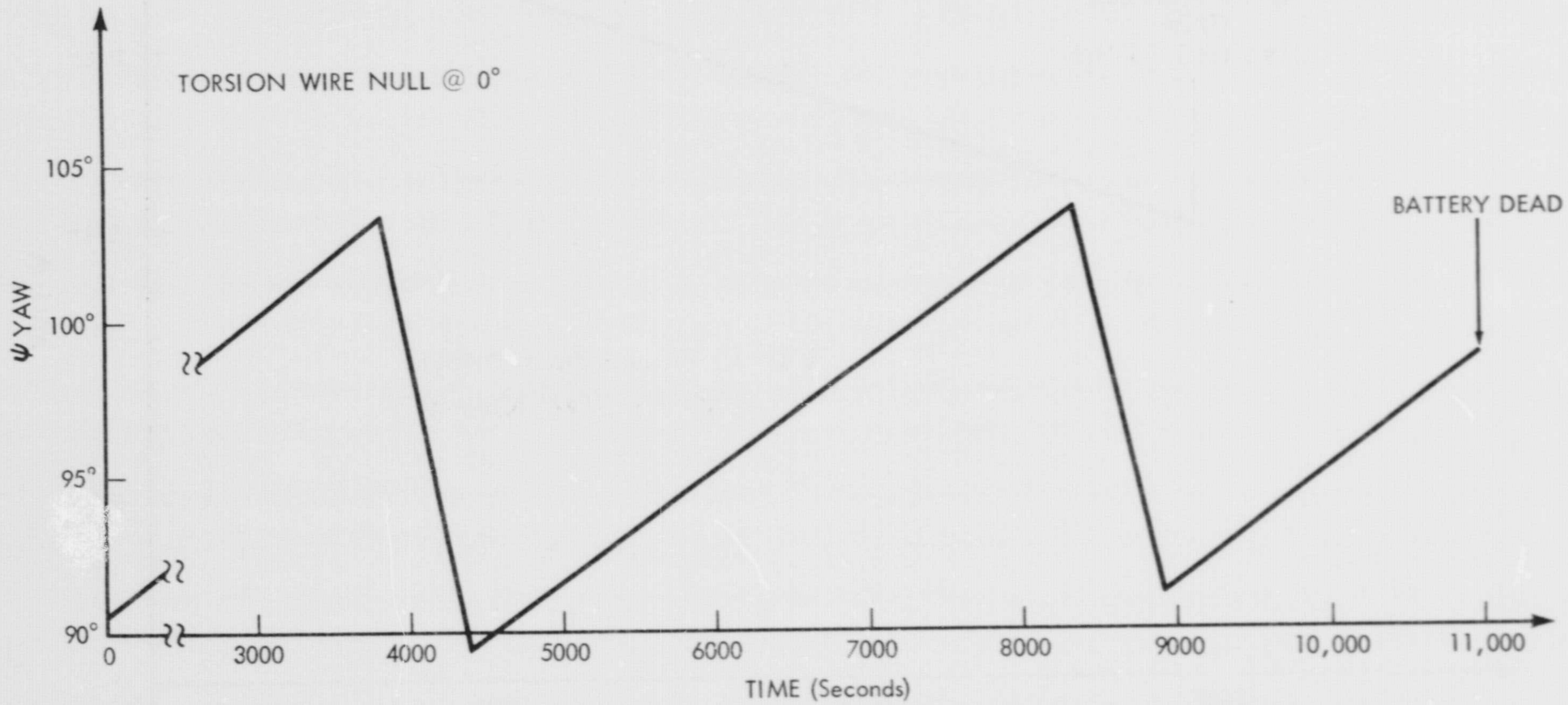

Figure 11. Yaw Fine Control Run V

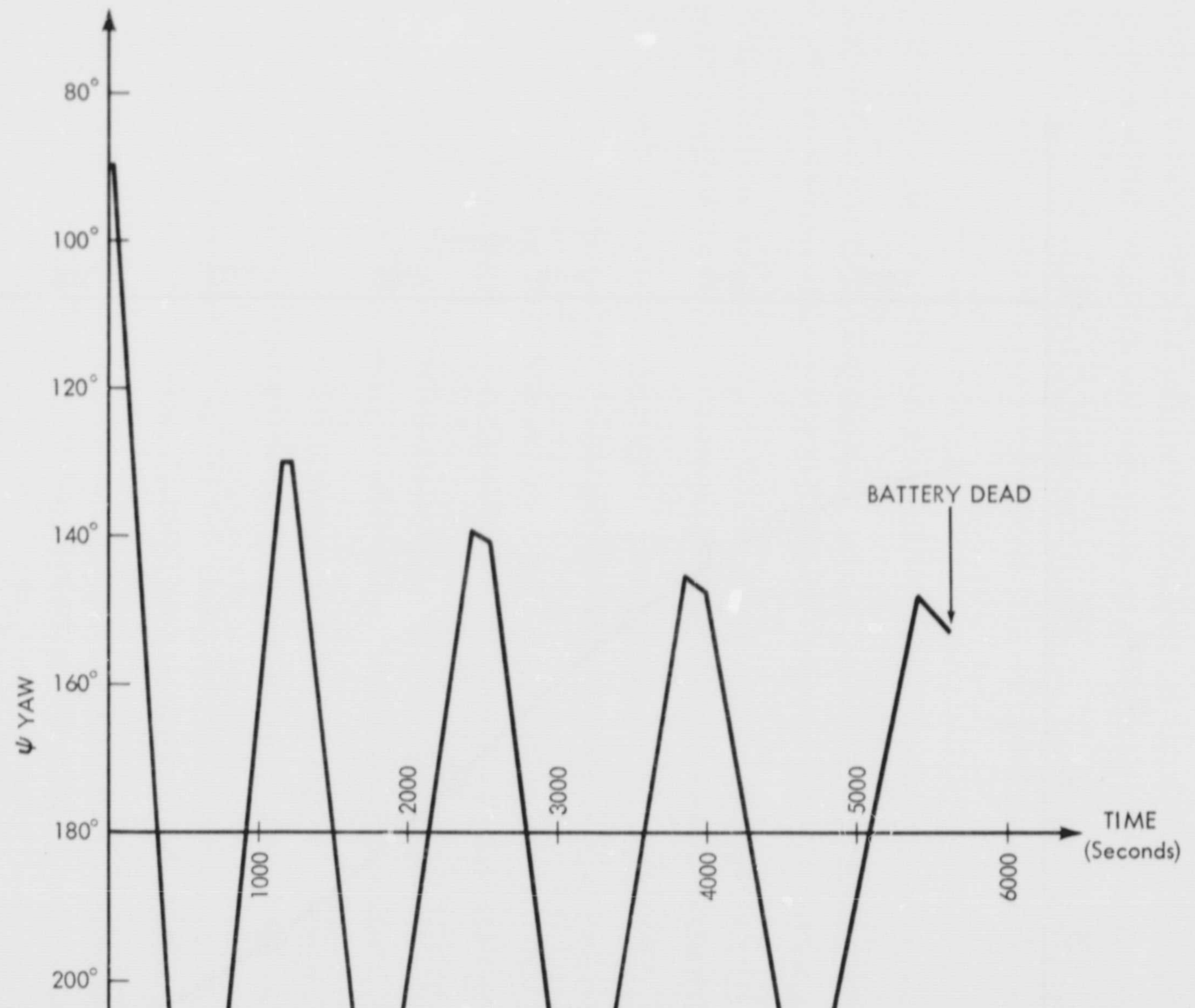

Figure 12. Yaw Fine Control Run VI

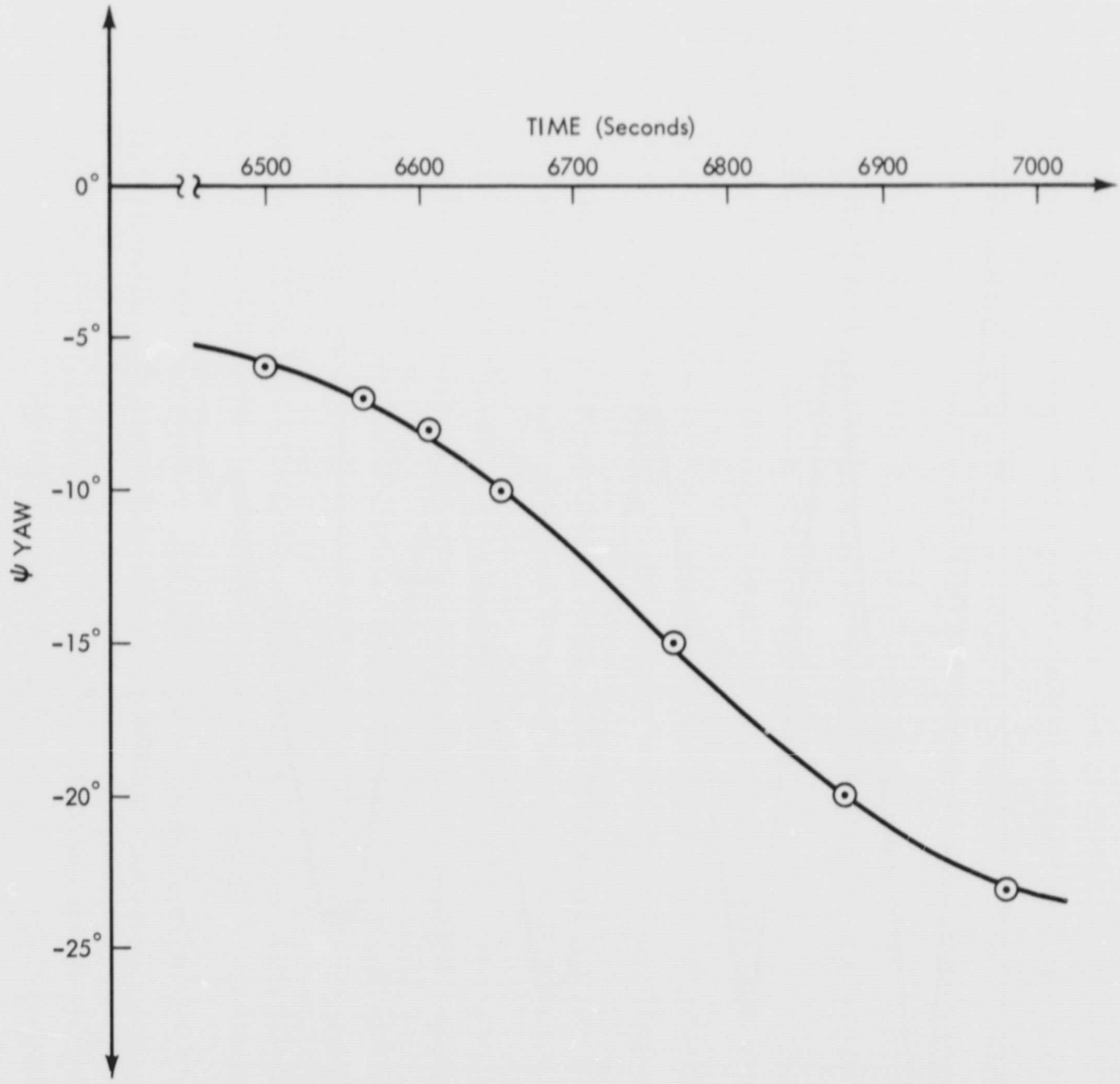

Figure 13. Detail of Run III, Yaw Fine Control

Figure 14. Pitch Frequency Response